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SMALL-BREAK LOCA RECOVERY IN B&W PLANTS

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ABSTRACT

A break of approximately 0.0012 m^2 in the cold leg of a B&W plant results in an interruption of natural circulation when steam accumulates in the hot-leg U-bend. A small-break loss-of-coolant accident of this size was simulated by TRAC-PF1 to evaluate strategies for recovery and for re-establishing natural circulation. In the absence of operator action, core cooling occurs when water supplied by the high-pressure-injection system boils, then is discharged through the break. Raising the steam-generator secondary level, venting steam from the steam-generator secondary, venting steam from the hot-leg U-bend, "bumping" the reactor-coolant pumps, and injecting a portion of the high-pressure-injection system into the hot-leg U-bend aided in cooling and depressurizing the primary system but were ineffective in re-establishing natural-circulation flows in the primary-coolant loops.

INTRODUCTION

Analyses of loss-of-coolant transients for small cold-leg breaks in Babcock and Wilcox (B&W) plants indicate that natural circulation in the primary loops may be interrupted by steam that accumulates in the "candy canes" (hot-leg U-bends). A small-break loss-of-coolant accident (LOCA) was calculated with TRAC-PF1 (Ref. 1) to investigate the conditions for interruption of natural circulation, and to evaluate strategies for recovery and for re-establishing natural circulation. A small break (0.00121 m^2, 0.013 ft^2) was assumed to occur in one of the cold-leg pipes between the high-pressure injection system (HPIS) inlet and the vessel. This break size was selected to provide conditions for loss of natural circulation while the primary pressure remained relatively high. The calculations used "best-estimate" assumptions for the equipment performance and operator actions, except in the case of the HPIS, which was assumed to deliver approximately 70% of its rated capacity.

The response of the plant following a small-break LOCA was simulated to evaluate the effectiveness of the following operator actions in restoring natural-circulation cooling: (1) cooling and depressurizing by venting steam from the steam-generator secondaries, (2) "bumping" the main-coolant pumps, (3) venting steam from the upper elevations of the hot legs (candy canes), and (4) injecting a portion of the flow from the HPIS into the candy canes.

TRAC SIMULATIONS

TRAC Model

The break size for this study was selected to provide conditions for loss of natural-circulation cooling while the primary pressure remained relatively high. Figure 1 shows a TRAC noding diagram for the B&W lowered-loop model based on the Oconee plant. Loop A represents the loop with the cold-leg break and includes the hot leg with the pressurizer (component 22 in the figure), the steam generator, and two cold legs—one intact and one with the break. Each loop-A cold leg includes a loop seal, a pump, and a connection for the HPIS. The reactor coolant pumps were modeled using the Loss-of-Fluid Test Facility (LOFT) pump characteristics built into TRAC, but scaled with Oconee-pump data. The break is located in one cold leg between the HPIS connection and the vessel. Loop B represents the unbroken loop and is similar to loop A except that there is no break or pressurizer and the two cold legs are combined to increase calculational efficiency. The flow out the break was computed using the critical-flow model in TRAC-PF1.

The secondary side of each steam generator is attached to the main-feedwater inlet, to the auxiliary-feedwater inlet, and to the main steam line, which has a connection representing relief valves that vent to the atmosphere. Geometry and other plant data were obtained from the Final Safety Analysis Report[2] (FSAR) and other data sources for the Oconee-1 plant. The model for the auxiliary-feedwater (AFW) system allows flow to enter near the top of the steam generators, and the flow of auxiliary feedwater is controlled based on the water level in the secondaries.

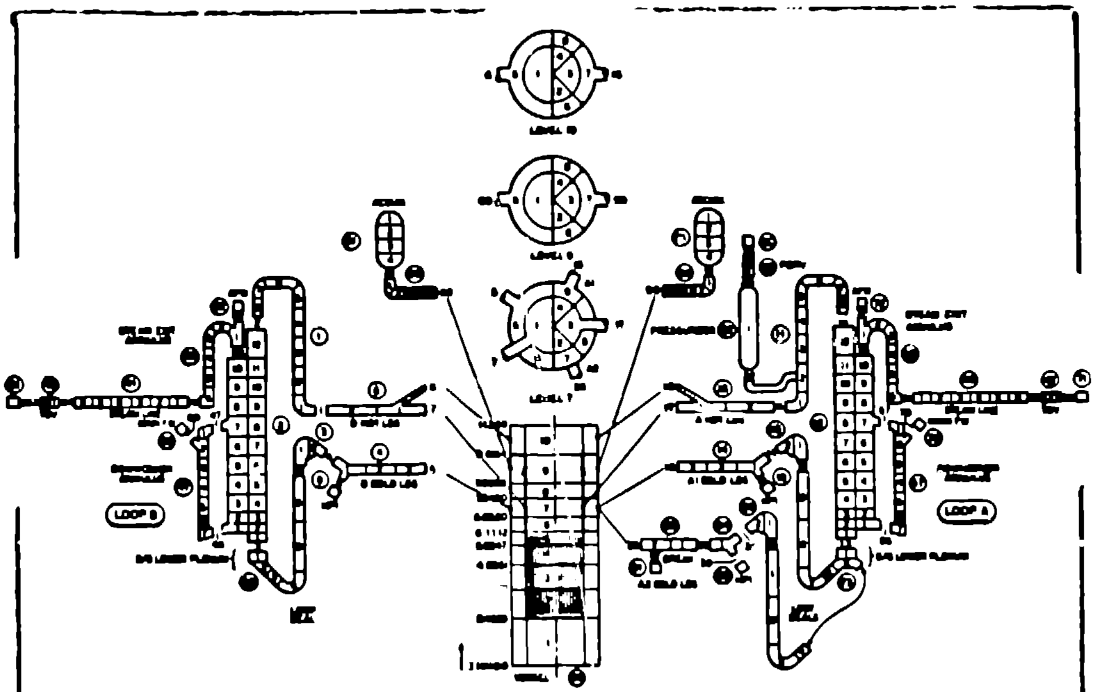

Fig. 1. TRAC Noding of a B&W PWR.

The vessel was modeled with 4 azimuthal segments, 2 radial egments, and 10 levels. The 10 levels include a lower plenum, 4 ctive core levels, 4 levels in the upper plenum to permit more recise tracking of the liquid level and for correct vent-valve levation, and an upper head. The model includes connections from he upper head to each hot leg to simulate the upper-head irculation observed by B&W in their flow tests. These onnections are needed because TRAC, with only a single radial ing in the upper plenum, models poorly the flow out of the core, hrough the center of the upper plenum, into the upper head, and ack into the upper plenum. Vent valves and connections for ccumulator injection into the downcomer are modeled in level 9 of he vessel.

ase Case

The plant response following a small-break LOCA was simulated ith TRAC to about 7000 s to establish the conditions for loss of atural-circulation flow and to investigate the effectiveness of mergency systems in cooling the core. During this time, the uxiliary feedwater was throttled to maintain the water level in he secondary side of the steam generators at 50% of the operating ange. The event sequence for this transient is given in Table 1, nd the primary pressure in Fig. 2. The calculation showed that the core remained covered and cooled. Figure 3 shows that the maximum average core temperature essentially follows the saturation temperature corresponding to the system pressure because the core is in the nucleate-boiling heat-transfer regime. The analysis showed that the core would be cooled (after loss of natural-circulation flow in the primary loops) by HPIS water injected into the cold legs, boiling of the water when it reaches the core, and discharging two-phase (steam/water) mixtures through the vent valves and out the break.

Recovery Strategies - Operator Initiated

The small-break LOCA calculation described in the previous section was restarted at 2000 s to simulate various operator actions to test their effectiveness in enhancing core cooling and in recovering natural-circulation flow. The first action was to increase the steam-generator secondary water level from 50 to 95% of the normal operating range to create a condensing surface on the steam-generator primary side. That process required

Table 1. Small-Break LOCA Event Sequence for the Base Case

Time (s)	Action	Consequence
0.0	Small cold-leg break ($0.00121 m^2$, $0.013 ft^2$)	Primary pressure starts rapid decrease
42.1	Primary pressure at 13.1 MPa (1900 psia)	Reactor trip Main-feedwater pumps trip
56.0	Primary pressure at 11.14 MPa (1615 psia)	HPIS signal generated
72.1	AFW starts	Steam generators begin filling
91.0	HPIS begins delivering	
106.0	Reactor-coolant pumps trip	Natural-circulation flow established
670.0	Loop-A candy cane fills with steam	Natural-circulation flow stops in Loop A
760.0	Loop-B candy cane fills with steam	Natural-circulation flow stops in Loop B
4940.0	Accumulator injection begins	
7150.0	Terminate calculation	

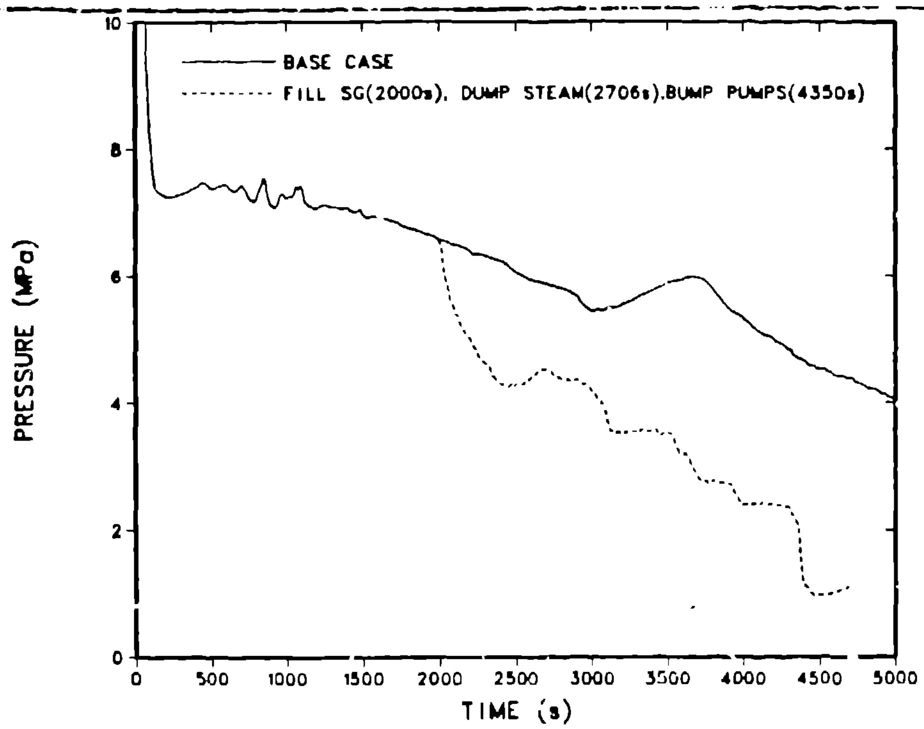

Fig. 2. Primary system pressure for the base case and for the operator-initiated cooling-and-recovery case.

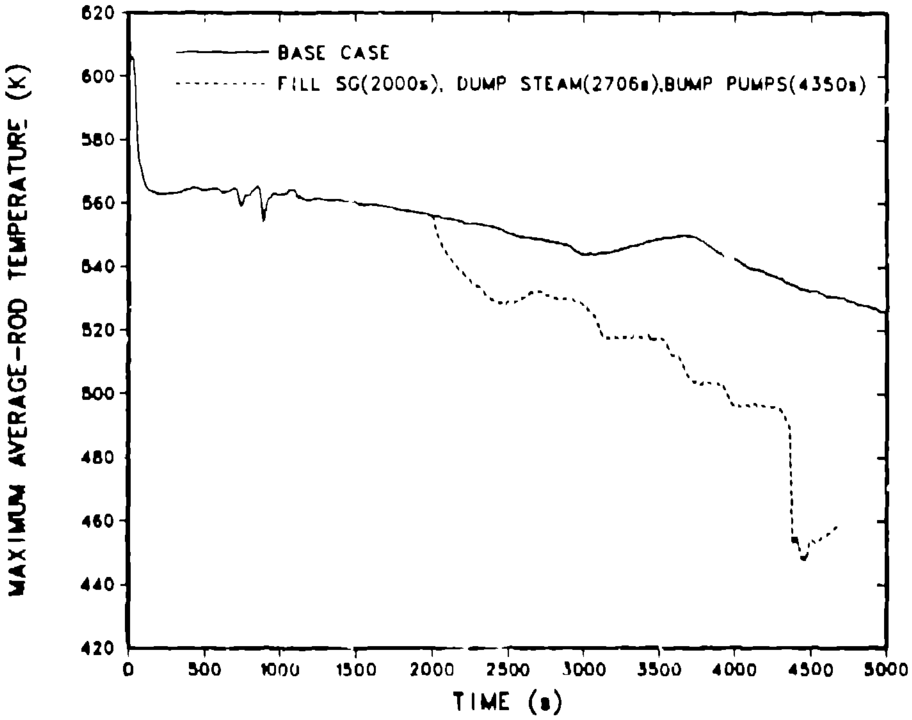

Fig. 3. The maximum temperature of the average fuel rod decreased more rapidly with operator-initiated actions.

approximately 550 s. The additional cold water on the secondary side lowered both the secondary- and primary-side pressures because of condensation. This can be seen in Fig. 2, which gives both the base-case and operator-initiated primary pressures. The lowered pressure in the steam generator increased the liquid level within the loop. That liquid was from three sources: water from the vessel, increased HPIS flow as the primary pressure decreased, and condensation in the steam generators. When the 95% steam-generator level was attained, the primary pressure began to increase.

At 2700 s steam was vented from the secondary side to continue the cooling process. The primary-to-secondary energy transfer resulted in a further decrease in primary temperature and pressure. This can be seen in Figs. 2 and 3, which give the primary pressures and the maximum fuel-rod temperatures, respectively. At 3006 s the primary pressure was reduced to the accumulator injection pressure. Water from the accumulator reduced the system pressure and temperature as steam condensed near the injection point at the top of the vessel downcomer. The water level in the loops did not increase significantly, however. In particular, the top of the hot-leg candy cane remained voided, as can be seen in Fig. 4.

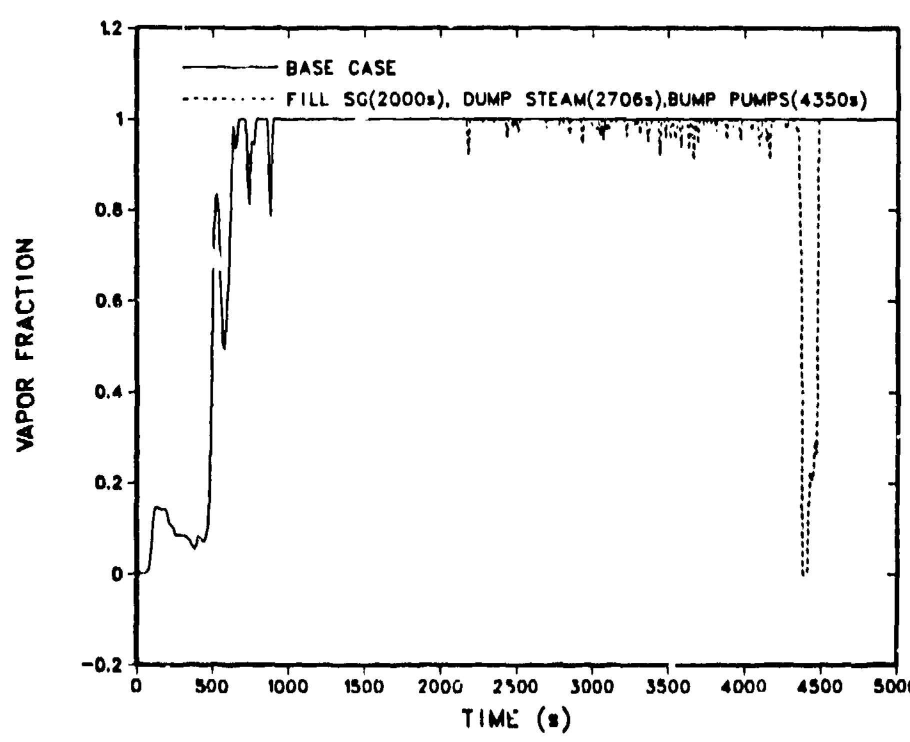

Fig. 4. Void fraction at the top of the candy cane for the base case and the operator-initiated cooling-and-recovery case.

At 4350 s the main coolant pumps were "bumped" or operated for 2 min to establish loop flow. Flow induced by the pumps rapidly mixed cold water in the cold leg with hotter water and steam in the upper part of the system, resulting in a pressure reduction. The pressure reduction, in turn, resulted in injection of 90% of the remaining accumulator water. The vessel inventory increased; but the top of the candy canes remained filled with steam except for the time when the pumps were running. Thus natural-circulation cooling flow could not be sustained in the loops. By 4500 s the system pressure was reduced sufficiently to allow the low-pressure injection system (LPIS) to operate. Thus stable cooling using the LPIS in a recirculation mode is possible.

In Table 2 the event sequence of the operator-initiated cooling-and-recovery case and the base case are compared. As can be seen in the table, the various operator actions increase the rate of cooling and depressurization, but, as in the base case, natural-circulation cooling flow in the loops was not established.

Table 2. Comparison of Events for the Base Case and Operator-Initiated Cooling and Recovery

Event	Time	
	Base Case (s)	Recovery (s)
Change steam-generator level control	-	2000
Steam generators fill to 95% level	-	2550
Open secondary-dump valves	-	2706
Accumulator injection begins	4940	3006
"Bump" reactor-coolant pumps	-	4350
Low-pressure injection attained		
- by bumping the pumps	-	4500
- without bumping the pumps	9800[a]	5100[a]
Re-establish natural-circulation cooling	-	-

[a]Estimated by extrapolating pressure.

In some auxiliary calculations with a similar model and an earlier version of TRAC-PF1 (version 7.6), two additional operator actions were simulated. The major differences in the plant model were that fewer axial levels were used in the vessel model (7 instead of 10) and an elevation difference was lacking between the reactor coolant-pump centerline and the cold-leg centerline (the elevation difference was 1.1 m in the former model). The simulated operator actions were:

1. venting steam from the upper elevations of the hot legs and

2. injecting a portion (10%) of the HPIS flow into the steam-filled candy canes.

Valves in the hot-leg candy canes normally are used to expel air from the primary and to facilitate refilling after a refueling outage. Because information on the valve dimensions was not provided, a diameter of 1 cm (0.394 in) was assumed for the orifice. The valves in both candy canes were opened fully 1600 s after natural-circulation flows ceased and remained open throughout the transient. Accumulator injection produced a sharp decrease in the vapor fraction in the upper plenum. However, the vapor fractions in the upper plenum were not changed significantly by opening the high-point vents.

The presence of valves at the top of the hot-leg candy canes affords the possibility of injecting cold liquid into these regions. To evaluate the effect of subcooled liquid introduced into the steam-filled candy canes, the calculations were restarted 1600 s after natural-circulation flows ceased; and 10% of the HPIS flow was injected into the candy canes of each loop, whereas the cold-leg injection flows were reduced to 90% of their original delivery rates. Dividing the HPIS flow between the cold and hot legs of each loop reduces primary pressure thereby enhancing the accumulator injection flows and refilling of the primary. The accumulators discharged about 19 m^3 of liquid in 1000 s. Only 12 m^3 were discharged during this time with all the HPIS flow supplied to the cold legs. When the transient was terminated, most of the mass lost through the break had been recovered by the combined injection of accumulators and HPIS; the level had not, however, increased to fill the candy canes. As with the other operator actions, these actions aided in cooling and depressurizing the primary system, but the system was not refilled sufficiently to allow the resumption of natural-circulation flow in the primary-coolant loops.

Cold-Leg Flow Oscillations

While analyzing the results of the auxiliary calculations with the earlier versions of the input and TRAC-PF1, an interesting and possibly important phenomenon was noticed.[3] Sometime after single-phase natural circulation ceased in the primary system, the loop flows in A-Loop began to oscillate as shown in Fig. 5. These oscillations appeared to be fairly regular, with a period of approximately 200 s and an amplitude of approximately 100 kg/s. The liquid temperatures in the A-loop also oscillated in conjunction with the flows. The amplitude of the temperature oscillations was approximately 40 K. As a result of detailed analysis of the flows and pressures in the A-Loop during the time the oscillations occurred, it became evident that the differential head term (ρgh) in the momentum equation was dominant. Before the oscillations began, the preferential flow direction was from loop A2 to loop A1 (loop A1 flow is positive into the vessel; loop A2 flow is negative away from the vessel - refer to Figs. 1 and 5), and this flow direction corresponds to the differential head (ρgh) calculated around the loop as shown in Fig. 6. A positive elevation head around the loop implies the differential head term in the loop seal of loop A2 is greater than the differential head of loop seal A1. Therefore, the density in loop seal A2 is greater than in loop seal A1 because the elevations are the same. When the oscillations began at about 2250 s, the differential head became negative as shown in Fig. 6. This means the density in loop seal A2 became less than in loop seal A1. When this occurred, the flow directions in the loop reversed as shown in Fig. 5. A comparison of Fig. 6 to Fig. 5 shows that the differential head does indeed lead the flow; this implies the differential head variations in the loop seal are what drive the flow oscillations.

The oscillations occurred as follows. When natural circulation stopped, the pressure gradient between the downcomer and upper plenum reversed and the vent valves opened. Then, relatively warm fluid (both liquid and vapor) passed from the upper plenum to the downcomer. The upper plenum fluid temperature was approximately 550 K. The warmer upper plenum fluid began to mix with the colder downcomer fluid, and the vessel source temperature to loop A2 increased. After 2250 s, relatively warm water flowed into loop A2 from the vessel. The warmer fluid in loop A2 eventually brought the temperature in loop seal A2 to a higher temperature than in loop seal A1, at approximately 2250 s. This caused the differential head in loop seal A2 to be less than the differential head in loop seal A1 as shown in Fig. 6. Thus, the flow direction changed as shown in Fig. 5. When the flow direction changed, warmer liquid was drawn into the A1 loop from the vessel. Cold HPIS liquid preceding the warmer vessel liquid into the loop seal provided a restoring (an additional component to the density difference) force and maintained the oscillations.

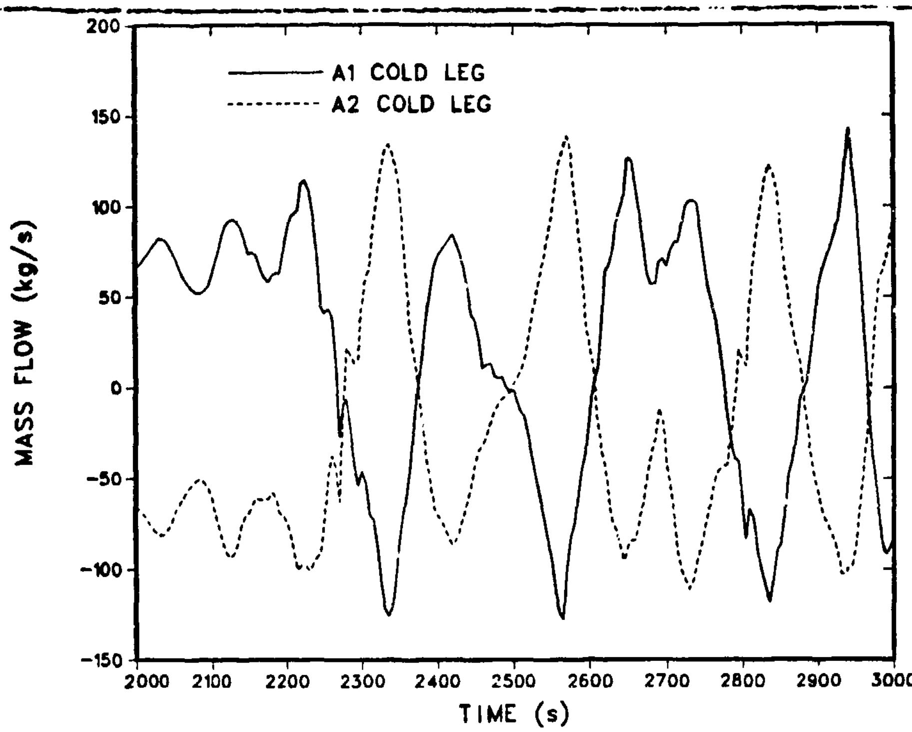

Fig. 5. Cold-leg flows at the pump exits.

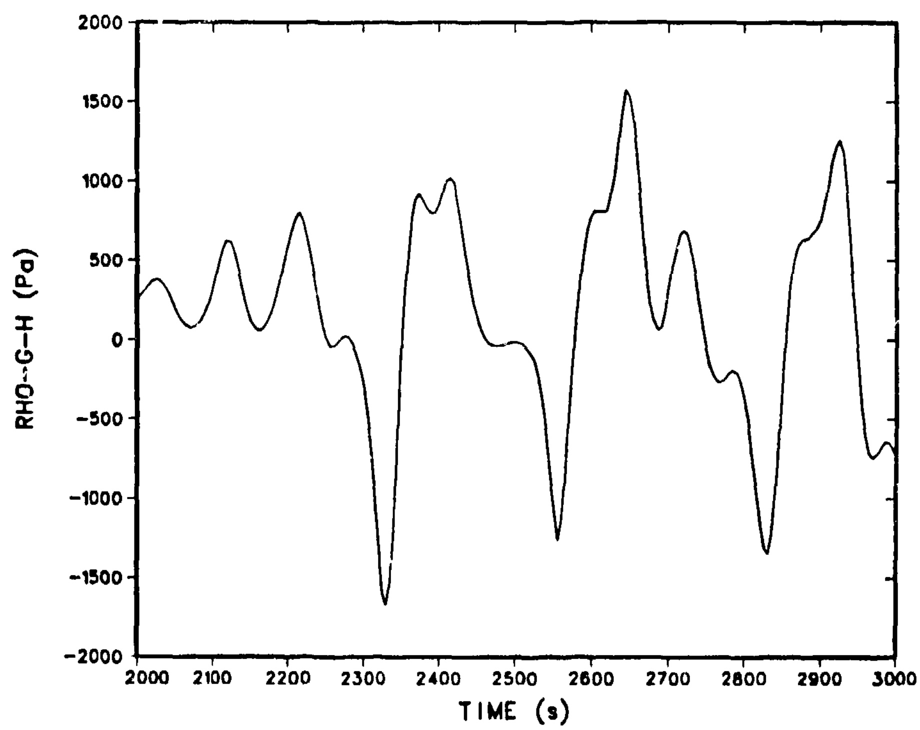

Fig. 6. Net differential head around loop A cold legs during the oscillations.

When the correct pump centerline elevation was included in the newer model, the density differences for this particular transient in the loop seal were insufficient to reverse flow; thus, the split cold-leg flow remained unidirectional (no oscillations occurred following the lose of natural circulation). Within the limitations of TRAC one-dimensional modeling, it remains possible that oscillations can be produced with different conditions in the transient such as a larger temperature (hence, density) difference between the liquid in the vessel and the liquid in the cold leg.

Within the limitations of TRAC one-dimensional modeling, the oscillations are real. However, these flow oscillations may not occur in an actual plant because of multidimensional effects. These effects could allow the cold HPIS liquid to settle to the bottom of the loop seal whereas the warmer fluid would flow countercurrent to the HPIS liquid and settle toward the top of the loop seal because of the density gradient.

CONCLUSIONS AND RECOMMENDATIONS

From our analyses of small-break LOCA behavior, we conclude that:

1. For the break size analyzed (0.0012 m^2), single-phase natural-circulation flow is interrupted because of hot-leg voiding in the candy-cane region.

2. The interrupted natural circulation could not be restored by the formation of a condensing surface in the steam generators, by venting secondary steam, by venting steam from the primary, by injecting HPIS liquid into the candy canes, nor by "bumping" the reactor coolant pumps.

3. Adequate core cooling is maintained by internal circulation through the vent valves and by decay heat removal through the break.

We recommend that multidimensional modeling of the loop seals be performed to determine the accuracy of the TRAC one-dimensional model. Also, experimental investigation of the loop-oscillation phenomenon should be conducted at a reasonable scale to verify code predictions. Further, TRAC analyses are proposed to investigate the range of break sizes for which the recovery strategies are effective and to verify the recovery procedures recommended by B&W to restore natural circulation. The ultimate goal of these analyses is to define the plant conditions necessary for re-establishing and maintaining natural circulation during small-break LOCAs in B&W plants.

REFERENCES

1. Safety Code Development Group, "TRAC PF1, An Advanced Best-Estimate Computer Program for Pressurized Water Reactor Analysis," Los Alamos National Laboratory report (in preparation).
2. "Final Safety Analysis Report, Oconee Nuclear Station, Units 1, 2 and 3," Duke Power Co. (May 1969).
3. J. R. Ireland and R. J. Henninger, "Analyses of B&W Small-Break LOCA TRAC Calculations", Los Alamos National Laboratory report LA-UR-82-3294 (November 1982).